Reply

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We thank Dr. Robinson for his comments. Robinson argues that the results of Cash et al. (2002) (hereafter CKV) are not inconsistent with the presence of an annular mode (AM) in the numerical model used. He suggests that the zonally asymmetric character of CKV's AM events is due to the superposition of independent annular and non-annular features, with AM's being (presumably) a real dynamical phenomenon independent of the zonally asymmetric eddying motion. However, while it may be impossible to rule out the presence of such an AM in the CKV experiments, we do not believe that the AM's, thus interpreted, necessarily best represent the underlying dynamical behavior of the model.

The AM problem has descriptive aspects and dynamical aspects. In CKV, we look for useful statistical descriptions of the spatial structure of extratropical atmospheric low-frequency variability in an aquaplanet model. We calculate the leading EOF of the hemispheric-wide surface pressure and the leading EOF of the zonal-mean surface pressure. We find that these two structures have practically identical *meridional* structures (Fig. 1): that is, the zonal mean of the hemispheric-wide surface-pressure EOF is the same as the EOF of the zonal-mean surface pressure.

The meridional structure of the AM's is similar to the zonal-mean of circulation anomalies in smaller zonal sectors. One way of seeing this is to calculate the leading EOF of the surface pressure in a 90-degree longitude sector (CKV Fig. 11). The zonal mean of this structure, shown as a dotted line in Fig. 1, is also very similar to the other two curves in the figure. Another way to obtain maps of characteristic localized circulation anomalies is to calculate the teleconnection patterns in the surface pressure. These are structures with a characteristic longitudinal scale of about 90 degrees. As can be inferred from CKV Figs. 9a-b, these also have an AM-like meridional structure, with maxima and nodes appearing at similar locations to those in Fig. 1. Thus, the meridional structure seen in the zonal-mean AMs is quite robust and appears using several different analysis techniques.

The meridional dipole structure in Fig. 1 is characteristic of the zonal-mean anomalous circulation on various timescales. It can be seen in snapshots of the zonal-mean flow as well as in long-term composites over high- or low-AM index periods (not shown). This is because it is related to the position of the model's zonal-mean circulation: for example, when the model's AM index is positive, the zonal-mean circulation is shifted polewards. We conclude that the meridional structure of the hemispheric-wide EOF - that is, of the AM – is both robust and representative of typical zonal-mean circulation anomalies.

This conclusion does not extend to the *two-dimensional* structure of the AM. This structure is too zonally symmetric to well represent the two-dimensional flow on high- and low- AM index days. That is, in our model (CKV Fig. 7), the hemispheric-wide AM structure is not typically seen in snapshots of the low-pass filtered data. Furthermore, the zonal structure does not survive in the teleconnection plot (CKV Figs. 9a-b) or in the sector EOF (CKV Fig. 11, Ambaum et al. 2001). The teleconnection and the sector EOF, on the other hand, do have a similar localized zonal structure. We notice that in Robinson's model (his Fig. 1), more zonal structures are present on high index days, indicating that the eddy activity in his model is relatively weak. In general, however, the latitude-longitude map of the AM, at least in the lower troposphere, is not representative of the latitude-longitude flow patterns, and is therefore, perhaps, not a useful description of the low-frequency variability.

The sector EOF and the zonally localized teleconnection patterns may provide a more useful description of the two dimensional structure for two reasons. First, these patterns, with their characteristic northwest-to-southeast phase tilt, can be seen in typical snapshots of the two-dimensional flow (CKV Fig. 7). These patterns represent the typical zonally localized flow pattern that one would find on a given day in which the zonal-

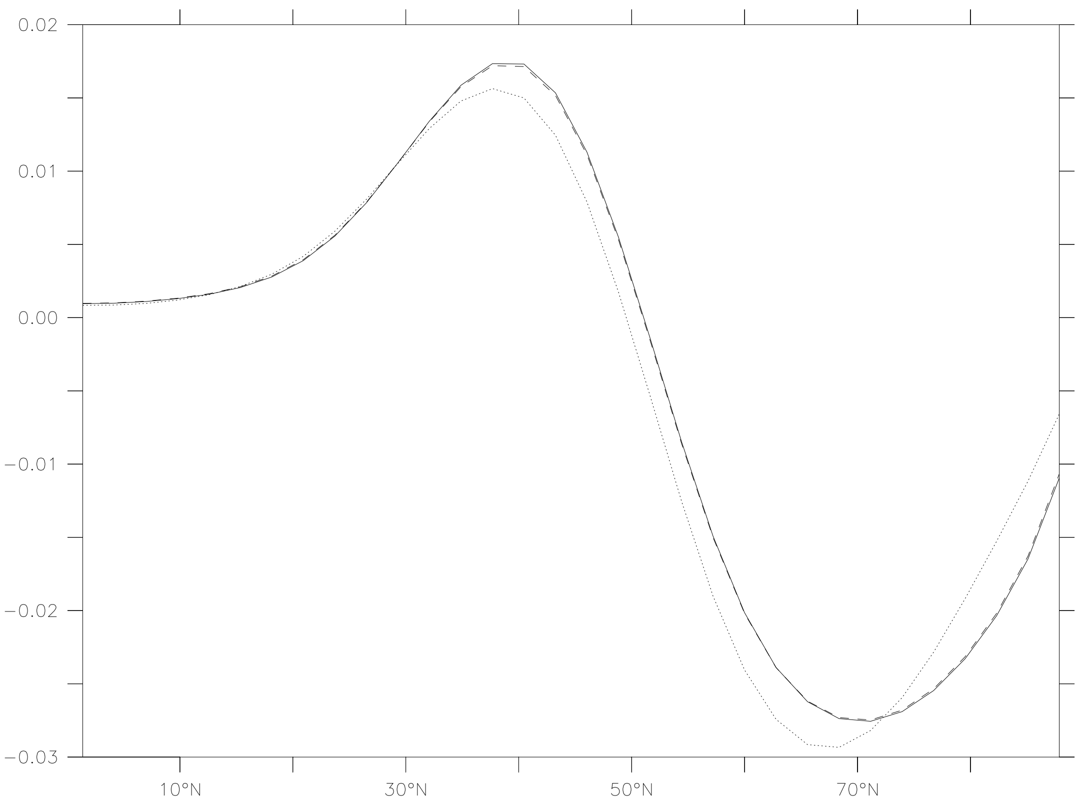

Figure 1: EOF of the zonal-mean surface pressure in the CKV model (solid). Zonal mean of the non-zonally averaged surface pressure in the CKV model (dashed). Zonal-mean of the sectoral EOF shown in CKV Fig. 11a (dot-dashed)

mean flow is in a high- or low- AM index state. Second, we find that the zonally localized structures are not unique to the zonally homogeneous CKV model. In Fig. 2, for example, we show the teleconnection patterns from three models that are strongly zonally inhomogeneous, because of land-sea contrasts and topographic forcing, as well as from the zonally homogeneous aquaplanet model (Cash et al., 2003, submitted to J. Atmos. Sci.). It can be seen that these structures are very similar among the various simulations, despite the wide variation in lower boundary conditions for these models.

Regarding the dynamical aspects of the AM problem, we agree with Robinson that only a fuller appreciation of the dynamics will lead to a better understanding of low-frequency variability of the extratropical general circulation and the relevance of AM's. Our current understanding is that much of this variability is forced by high-frequency transient eddies, consistent with Robinson's Fig. 3. Our analysis shows that, at least within our models, the high frequency eddy forcing gives rise to zonally localized circulation anomalies, whose structures are seen in the sector EOF or the teleconnection patterns — and that, as we have said, project onto the zonal mean (Fig. 3). Focusing on these regional patterns has lead to insights into the problem in zonally inhomogeneous models and in the observations. These ideas are discussed further in two studies under review (Vallis et al., 2003; Cash et al., 2003, both submitted to J. Atmos. Sci.).

We conclude, then, that the two-dimensional, hemispheric-wide AM is not a particularly illuminating way to represent the underlying dynamics. Such a structure arises from the EOF analysis and is not a dominant feature of the flow itself. Our understanding of zonal-mean AM dynamics could therefore, we believe, be improved by focusing on the local circulation anomalies associated with zonal-mean AM events.

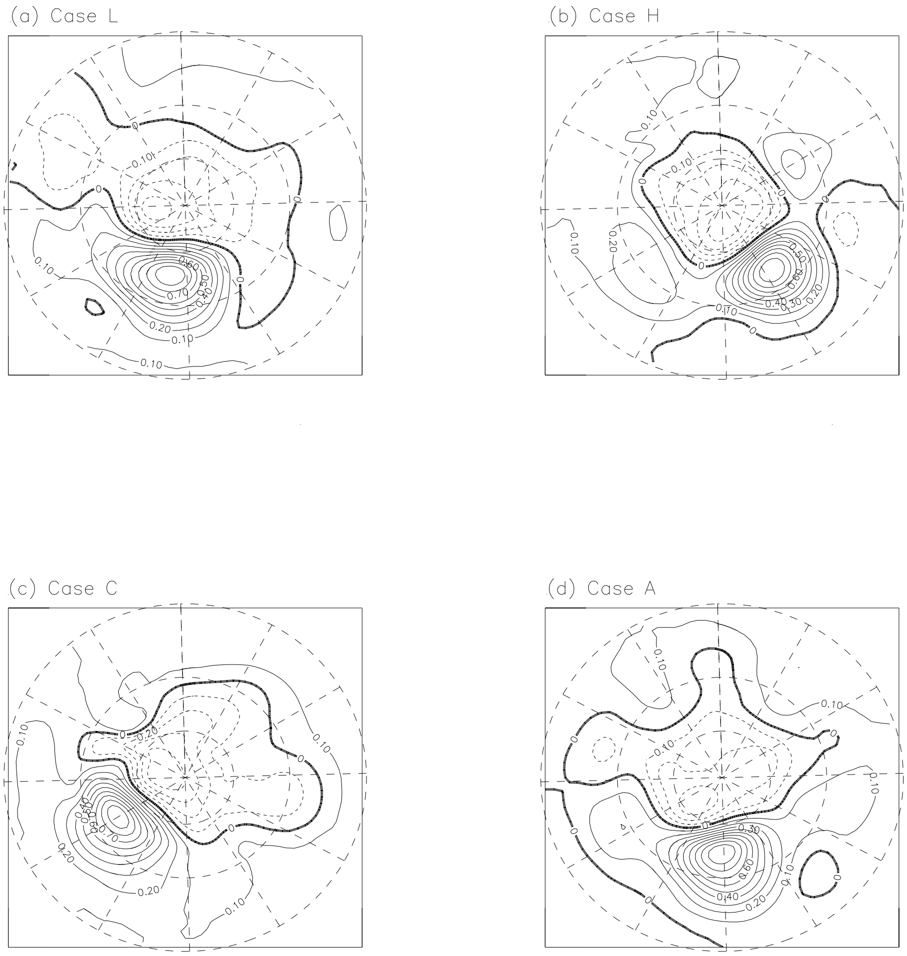

Figure 2: Surface-pressure teleconnection patterns for (a) Case ″L″, an integration in which the model has strong land-sea contrast and a flat lower boundary, (b) Case ″H″, with moderate land-sea contrast and moderate topographic forcing, (c) Case ″C″, with strong land-sea contrast and strong topographic forcing, and (d) Case ″A″, the aqua-planet model of CKV. Contours denote one point correlation maps. Contour interval is 0.l, and dashed contours are negative. (Cash et al. (2003), submitted to J. Atmos. Sci.)

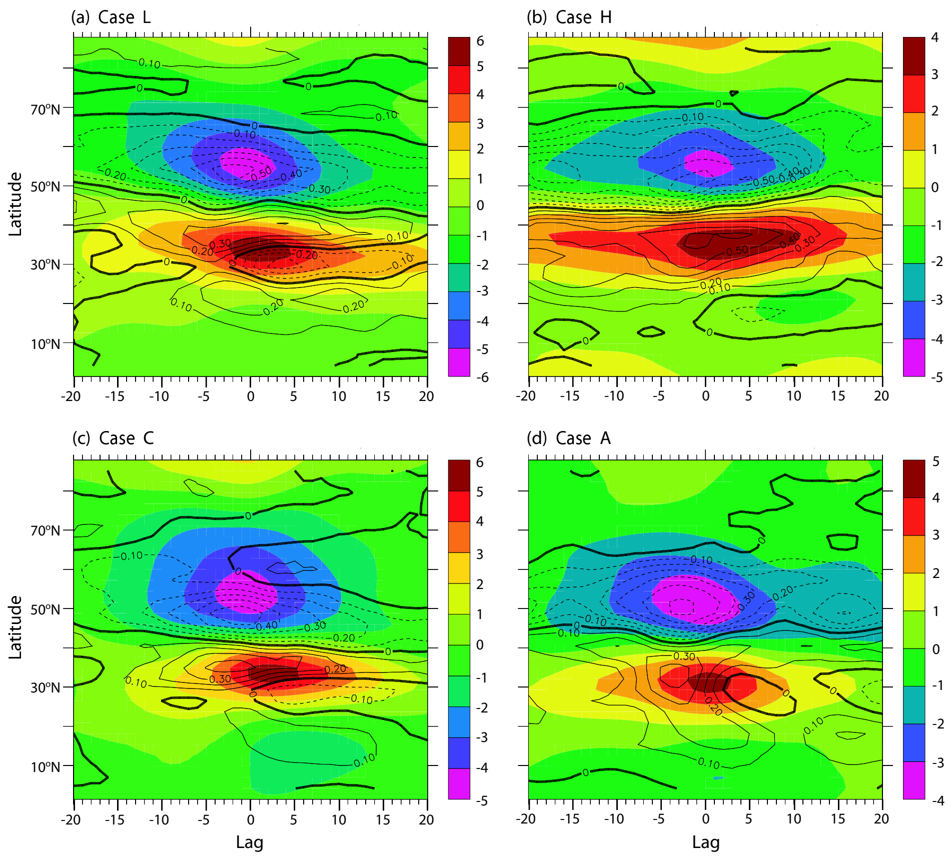

Figure 3: As in Fig. 2, for the regresssed zonally averaged zonal wind anomalies (shading) and anomalous eddy momentum flux convergences (contours). Units of wind are in ms^{-1}, units of momentum-flux convergence are in $ms^{-1}d^{-1}$.

References

Cash, B. A., P. J. Kushner, and G. K. Vallis, 2002. The structure and composition of the annular modes in an aquaplanet general circulation model. *J. Atmos. Sci.*, **59**, 3399–3414.

Cash, B. A., P. J. Kushner, and G. K. Vallis, 2003. Zonal asymmetries, teleconnections, and annular modes in a gcm. *J. Atmos. Sci.*, submitted.

Vallis, G. K., E. Gerber, P. J. Kushner, and B. A. Cash, 2003. A mechanism and simple dynamical model of the North Atlantic Oscillation and annular modes. *J. Atmos. Sci.*, submitted.